AD-A063 021 ARMY MATERIALS AND MECHANICS RESEARCH CENTER WATERTO--ETC F/G 11/6
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS.(U)
SEP 78 S V ARNOLD, R G HARDY

UNCLASSIFIED AMMRC-TR-78-52 NL

| OF |
AD
A063021

END
DATE
FILMED
3-79
DDC

AMMRC TR 78-52

SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS

STUART V. ARNOLD and RUSSELL G. HARDY
MATERIALS APPLICATION DIVISION

September 1978

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

Mention of any trade names or manufacturers in this report shall not be construed as advertising nor as an official indorsement or approval of such products or companies by the United States Government.

DISPOSITION INSTRUCTIONS

Destroy this report when it is no longer needed.
Do not return it to the originator.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(14)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AMMRC-TR-78-52	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): (6) SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS.	5. TYPE OF REPORT & PERIOD COVERED: (9) Final Report,
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s): (10) Stuart V. Arnold and Russell G. Hardy	8. CONTRACT OR GRANT NUMBER(s): (16)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, DRXMR-K	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: D/A Project: 1T162105AH84, AMCMS Code: 612105.11.H8400, Agency Accession: DA OG4673
11. CONTROLLING OFFICE NAME AND ADDRESS: U. S. Army Materiel Development and Readiness Command, Alexandria, Virginia 22333	(11) 12. REPORT DATE: September 1978; 13. NUMBER OF PAGES: 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 24p.	15. SECURITY CLASS. (of this report): Unclassified; 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Penetrators
Depleted uranium
Alloy segregation
Uranium alloys

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(SEE REVERSE SIDE)

403 105

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

LB

Block No. 20

ABSTRACT

Heats of three depleted uranium alloys were melted to nominal compositions as follow:

(a) U-0.75%Ti;

(b) U-0.75%Mo-0.75%Nb-0.75%Zr-0.3%V-0.5%Ti;

(c) U-0.85%Mo-0.85%Nb-0.5%Ti.

The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

DEPARTMENT OF THE ARMY
ARMY MATERIALS AND MECHANICS RESEARCH CENTER
WATERTOWN, MASSACHUSETTS 02172

DRXMR-PR

2 February 1979

SUBJECT: Errata - Technical Report Entitled "Segregation in Ingots of Lean Uranium Alloys"

See Distribution List Attached

1. The subject report by Stuart V. Arnold and Russell G. Hardy was incorrectly numbered AMMRC TR 78-41. It is requested that all copies of the report be changed to show the correct number:

AMMRC TR 78-52

on the front cover, DD Form 1473, abstract cards, and back cover.

2. The following corrections should be made in the text.

a. Page 2, twelfth line from bottom should read: "and-aged (STA) conditions. The STA samples were heated in vacuum to 1560 F and held".

b. Page 8, first two lines of fourth paragraph should read: "Because the mechanism of hardening these alloys is precipitation of the U_2Ti intermetallic,[4] it follows that prior depletion of titanium by scavenging carbon".

FOR THE DIRECTOR:

A. V. GALLAGHER
Chief, Technical Reports Office

INTRODUCTION

Development of long-rod penetrators fabricated from experimental alloys of depleted uranium (DU) has been hampered by erratic results obtained in ballistic evaluation of test projectiles. In accordance with a decision to examine penetrator processing history in search of factors responsible for the erratic ballistic performance, a sequence of research efforts has been planned, the first of which is this study. The objective of research reported herein was to characterize DU ingots of selected alloys melted at AMMRC to determine distribution of constituents, i.e., to detect and measure both macro- and microsegregation. If either was found to be present in the test ingots, process parameters were to be explored and practice modified to improve uniformity. Producibility was to be considered, both to reduce cost and to increase reliability.

APPROACH

Originally the plan called for characterization of ingots melted to two DU alloy compositions, but midway through the program a third alloy was added. Nominal compositions of the three alloys are given below:

a. U-0.75%Ti (hereafter U-3/4 Ti)

b. U-0.75%Mo-0.75%Nb-0.75%Zr-0.3%V-0.5%Ti (hereafter U-3/4 Quint)

c. U-0.85%Mo-0.85%Nb-0.5%Ti (hereafter U-Mo/Nb/Ti)

The extent of macro- and microsegregation in ingots melted by the practices developed at AMMRC was to be determined analytically and metallographically. Procedures were planned for exploring process parameters and modifying practice to enhance uniformity, if such enhancement were shown to be necessary. To correlate ballistic behavior with metallurgical characteristics, ingots would be extruded into bar stock, the bar stock would then be sectioned into blanks and heat treated, then penetrators would be machined from the blanks and tested. If, because of segregation, satisfactory and uniform ballistic behavior could not be achieved with the selected alloys despite modification of practice, revision of composition to reduce or delete segregating constituents was to be undertaken.

Because carbon content has been identified as a factor affecting heat treatment and mechanical properties,[1] it was planned to investigate two levels in this research, nominally 0.0050% and 0.0100% by weight, and optimize in a follow-on program if a need became apparent.

All heats were vacuum-induction-melted in a graphite crucible and bottom-poured into slightly tapered graphite molds to produce ingots 4-1/2 inches in diameter by 22 inches in height, weighing approximately 220 pounds. All graphite surfaces to be in contact with the molten metal were previously coated with a zirconia wash. "Small" heats for a single ingot and "large" heats, from which

1. JACKSON, R. J. *Metallographic Study of Segregation in Uranium-Base Niobium Alloys.* Metallography, v. 6, no. 4, 1973, p. 347-359.

two ingots were poured simultaneously through a tundish, were melted. This deliberate difference in practice introduced several variables as follows: (1) degree of inductive coupling; (2) difference in submerged crucible surface wet by the melt; and (3) ingot cooling rate (since two ingots are cooled in close proximity in the double mold used for the "large" heats.

One ingot from each heat was sectioned transversely to remove a 1/2-inch slice one inch above the bottom and another 1/2-inch slice some 14-1/2 inches higher (leaving a 14-inch cylindrical blank from which an extrusion billet would later be machined). Samples were taken from both slices at center, midradius and near-surface positions for analysis and metallography. The remaining upper portions of the ingots were sectioned axially and inspected for evidence of centerline shrinkage. Samples were analyzed chemically for metallic additives and for carbon, oxygen, hydrogen, and nitrogen.

Samples from the midradius position of the transverse slice adjacent to the top of the 14-inch billet blank were prepared for examination with an electron probe. These samples were taken from ingots of each composition in the normal carbon range (50 to 60 ppm) only. Samples of each composition were submitted (a) as-cast and (b) solution-treated-and-aged. A contract was placed with ManLabs, Inc., under Purchase Order DAAG46-77-M-1380 to develop and demonstrate a suitable technique using a specimen from the top surface location of an ingot of U-3/4 Quint, heat 165.

After some experimentation the contractor established a procedure and ran distribution scans for molybdenum, niobium, and zirconium using L α (1) peaks and for vanadium and titanium using K α (3) peaks; scanning rate was 625 μ/minute traversing a 1-cm path. The contractor concluded "It can be seen from these charts that no significant variations in composition were detected, indicating absence of coring." However, scans for zirconium and vanadium content were not appreciably different from background. It was decided to supplement the above procedure by scanning a 100-μ path at a 12.5 μ/minute traverse rate in order that the extent and scale of microsegregation be further detailed. The path for slow traverse was selected (1) to cross microstructural features; a representative grain boundary chosen by metallographic examination and (2) to avoid obvious inclusions. Under follow-on Purchase Order DAAG46-77-M-1732 the contractor surveyed samples taken from the top surface locations of ingots from heats 163, 164, and 188; samples from each heat were provided in both as-cast and solution-treated-and-aged (STA) conditions. The STA samples heated in vacuum to 1560 F and held 1/2 hour. The furnace was then back-filled with inert gas. As soon as the furnace temperature recovered to 1560 F, the samples were water quenched, and then aged 1/2 hour at 850 F in vacuum and furnace cooled.

Prior to scanning with the electron probe, samples were mounted and polished and examined metallographically in the unetched condition. Attempts were made to reveal evidence of coring by electrolytically etching the samples in accordance with procedure recommended by R. J. Jackson[1] but no indications resulted. A second (chemical) etching technique also showed no coring, but did disclose microstructure. This chemical etching method was used to identify features for slow traverse scanning. Etchant consisted of 10% by weight ammonium difluoride and 10% hydrofluoric acid in water at 45 C.

The principal purpose of scanning was to disclose local differences in metal composition; identification of inclusions was incidental.

DISCUSSION OF RESULTS

Macrosegregation in ingots of the three compositions can be judged by inspection of analytical data presented in Table 1. Since all heats (small, low-carbon heat 162; large, low-carbon heat 163; and large, high-carbon heat 179) are of the U-3/4 Ti composition, their data may be compared. Heat 162 is somewhat anomalous in that the quantity of metal cast was less than adequate for removal of a 14-inch section free from some pipe defect at the top end. This fact is responsible for high titanium, carbon, oxygen, and nitrogen values at top center and midradius positions. Metallographic examination showed that metal in the vicinity of the pipe contained many inclusions and some porosity. The majority of inclusions were angular, metallic-appearing titanium cyano-nitride, Ti(C,N); the remainder were rounded and translucent, presumably oxides (see Figure 1). The Ti(C,N) inclusions are commonly observed in this alloy, but are generally quite small and widely scattered, rather than larger and numerous as in this instance.

An ingot from large heat 163 shows no macrosegregation of titanium and low levels of carbon, oxygen, hydrogen, and nitrogen throughout. An ingot from large heat 179, intentionally melted to the higher carbon level, shows titanium and carbon slightly higher in the bottom ingot positions (see discussion of heat 173 below). Except for the bottom surface position, oxygen analyses are low and uniform. Hydrogen is low and uniform. Nitrogen is very low and uniform.

Assuming that carbon in the melt combines with titanium, it might be expected that higher carbon would lead to greater depletion of titanium dissolved in the melt. However, the titanium content of the high-carbon heat 179 was not lower than the titanium content of the lower-carbon heats 162 and 163. The oxygen, hydrogen, and nitrogen levels are appreciably lower in the high-carbon heat 179 than in heats 162 and 163 which contained normal levels of carbon (excepting the piped area of the ingot from heat 162). This cannot be attributed to the charge material with oxygen contents of 52 ppm for heat 162, 52 ppm for heat 163, and 49 ppm for heat 179.

It is possible that higher carbon affected oxygen removal. Avery,[2] who melted and cast small heats of uranium to which 0.60 or 0.90 percent by weight of titanium was added, shows an instance where high oxygen/nitrogen addition (>300 ppm) seemingly brought about carbon removal without influencing titanium recovery (compare alloys 5 and 7, Table 2). However, other data of his do not show similar behavior (compare alloys 4 and 6). The data are insufficient to justify intensive analysis. The possibility of interaction should be considered, nevertheless, since a modest "boil" ocassionally observed during melting indicates some gas evolution.

Small, low-carbon heat 164 and large, low-carbon heat 165 are of the U-3/4 Quint composition and their analytical data are suitable for comparison. The

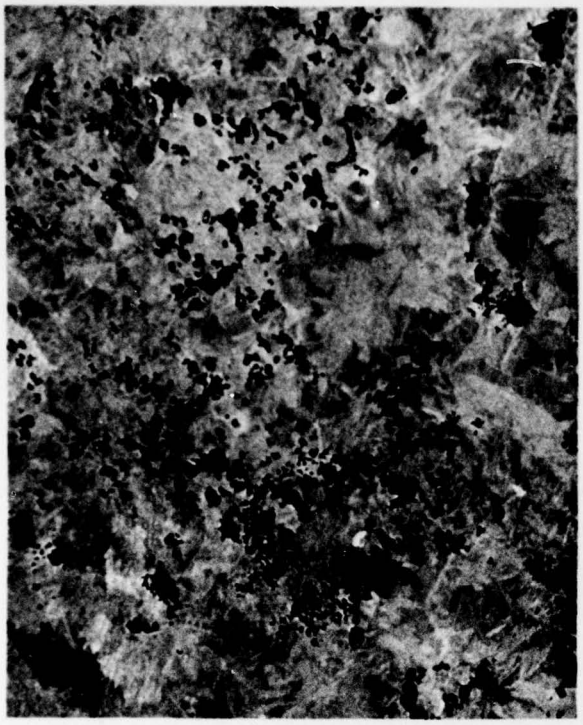
2. AVERY, J. G. *The Effect of Alloy Content, Carbon, Oxygen, and Nitrogen on the Mechanical Properties of Uranium - 2.2% Niobium and Uranium - 0.75% Titanium Wrought Heat Treated Alloys.* US AEC RFP-1950, March 1973, p. 6.

Table 1. COMPOSITION OF INGOTS FROM EXPERIMENTAL HEATS OF DEPLETED URANIUM ALLOYS FOR LONG-ROD PENETRATORS

Heat/Ingot Number, (Pour Weight)	Sample Location		Elements (Weight Percent)								
			Mo	Nb	Zr	V	Ti	C	O	H	N
162	Top	Center*	-	-	-	-	1.04	0.0299	0.0488	0.00043	0.0510
(177 lb)		Midradius†	-	-	-	-	0.89	.0233	.0320	.00018	.0225
		Surface	-	-	-	-	.64	.0065	.0052	.00015	.0026
	Bottom	Center	-	-	-	-	.62	.0032	.0034	.00022	.0032
		Midradius	-	-	-	-	.61	.0037	.0054	.00018	.0018
		Surface	-	-	-	-	.61	.0047	.0032	.00030	.0032
163	Top	Center	-	-	-	-	.67	.0044	.0054	.00018	.0021
(465 lb)		Midradius	-	-	-	-	.67	.0037	.0042	.00016	.0032
		Surface	-	-	-	-	.67	.0032	.0038	.00010	.0035
	Bottom	Center	-	-	-	-	.68	.0034	.0035	.00026	.0044
		Midradius	-	-	-	-	.68	.0032	.0052	.00016	.0045
		Surface	-	-	-	-	.68	.0041	.0050	.00017	.0043
179	Top	Center	-	-	-	-	.66	.015	.0028	.00010	.0008
(457 lb)		Midradius	-	-	-	-	.66	.016	.0030	.00008	.0006
		Surface	-	-	-	-	.66	.018	.0026	.00008	.0007
	Bottom	Center	-	-	-	-	.68	.020	.0030	.00009	.0008
		Midradius	-	-	-	-	.68	.024	.0033	.00011	.0008
		Surface	-	-	-	-	.69	.019	.0046	.00010	.0007
164	Top	Center	0.83	0.81	0.79	<0.4	.51	.0044	.0050	.00011	.0018
(449 lb)		Midradius	.74	.77	.75	.4	.49	.0048	.0041	.00011	.0015
		Surface	.84	.78	.78	.4	.52	.0053	.0043	.00010	.0028
	Bottom	Center	.80	.76	.74	.4	.52	.0043	.0072	.00012	.0018
		Midradius	.77	.79	.77	.4	.51	.0042	.0058	.00012	.0022
		Surface	.73	.75	.72	.4	.50	.0038	.0050	.00012	.0021
165	Top	Center	.85	.79	.77	.4	.52	.0038	.0054	.00014	.0018
(190 lb)		Midradius	.86	.82	.75	.4	.52	.0045	.0052	.00014	.0024
		Surface	.89	.85	.81	.4	.52	.0046	.0072	.00008	.0016
	Bottom	Center	.80	.77	.75	.4	.51	.0045	.0048	.00010	.0024
		Midradius	.86	.83	.81	.4	.52	.0042	.0057	.00010	.0024
		Surface	.71	.74	.67	.4	.51	.0044	.0044	.00009	.0031
184	Top	Center	.74	.74	.65	.16	.53	.0060	.0040	.00011	.0007
(440 lb)		Midradius	.75	.79	.69	.16	.56	.0040	.0038	.00009	.0007
		Surface	.75	.80	.68	.17	.55	.0070	.0037	.00013	.0014
	Bottom	Center	.75	.73	.69	.16	.53	.0090	.0068	.00017	.0030
		Midradius	.73	.76	.68	.16	.54	.0070	.0063	.00010	.0020
		Surface	.74	.74	.68	.16	.55	.0090	.0064	.00021	.0020
173	Top	Center	.84	.73	-	-	.30	.011	.0024	.00005	.0010
(447 lb)		Midradius	.85	.75	-	-	.29	.013	.0028	.00006	.0010
		Surface	.86	.74	-	-	.28	.013	.0024	.00012	.0010
	Bottom	Center	.83	.75	-	-	.35	.015	.0044	.00006	.0016
		Midradius	.86	.75	-	-	.35	.020	.0026	.00006	.0014
		Surface	.86	.76	-	-	.37	.021	.0052	.00006	.0017
188	Top	Center	.84	.80	-	-	.41	.006	.0036	.00010	.0015
(429 lb)		Midradius	.83	.80	-	-	.43	.004	.0034	.00008	.0007
		Surface	.84	.78	-	-	.43	.006	.0032	.00011	.0014
	Bottom	Center	.84	.81	-	-	.48	.011	.0039	.00012	.0028
		Midradius	.85	.81	-	-	.46	.011	.0041	.00009	.0036
		Surface	.84	.84	-	-	.48	.015	.0041	.00009	.0036

*Center defect
†Near center defect

{Ingot 162 weighed less and was shorter than all others. Accordingly, normal cropping did not remove pipe defect.



a. Top Center. Mag. 100X

b. Top Center. Mag. 500X

c. Bottom Center. Mag. 100X

Figure 1. Photomicrographs of unetched samples from top center showing piped area (a, b) and from bottom center (c) of Ingot 162.

Table 2. COMPOSITION OF URANIUM ALLOYS REPORTED BY AVERY[2]

Alloy	Composition	Ti, Wt%	C, ppm	O, ppm	N, ppm
4	Target	0.60	10-30	(O + N	200)
	Actual - Top	0.58	15	60	15
	Bottom	0.60	25	50	14
6	Target	0.60	150-200	(O + N	300)
	Actual - Top	0.50	60	55	10
	Bottom	0.51	40	50	15
5	Target	0.90	10-30	(O + N	200)
	Actual - Top	0.80	30	60	13
	Bottom	0.80	25	60	9
7	Target	0.90	150-200	(O + N	300)
	Actual - Top	0.79	32	40	15
	Bottom	0.79	17	60	5
8	Target	0.90	150-200	(O + N	200)
	Actual - Top	0.76	40	60	1
	Bottom	0.76	40	40	2

Ingots were vacuum induction melted and cast 3 inches in diameter x 9 inches in height. The top 3 inches were discarded. Samples were taken at bottom and top of the 6-inch portion which remained.

ingot from heat 164 shows an even distribution of metallic alloys and low, uniform carbon, oxygen, hydrogen, and nitrogen contents (excepting one anomalous oxygen value at bottom center position). An ingot from larger heat 165 is similarly uniform as regards distribution of metallics and carbon, oxygen, hydrogen, and nitrogen (possibly excepting certain metal values from the bottom surface sample). Again there is no evidence of macrosegregation.

A large, nominally high-carbon heat 184 of the U-3/4 Quint composition showed excellent uniformity of metallic additives. However, carbon (targeted at 0.015%) ran 0.007 to 0.009% in the bottom positions and 0.004 to 0.007% in the top positions. Oxygen content was unusually high in the bottom positions, but normal in the top. Nitrogen content was normal in the bottom positions, lower in the top positions. Titanium, which might have shown depletion, was anomalously high and uniform; zirconium, though uniform, was lower than expected.

In view of the 0.5% by weight changes, titanium analyses of heats 164, 165, and 184 seem questionable.

The U-Mo/Nb/Ti alloy is developmental and little melting experience with this composition has been acquired to date. Analytical data for large heat 173 shows the distributions of molybdenum and niobium are quite uniform throughout the ingot. Titanium is lower in the upper portion of the ingot, as also are carbon and nitrogen (and, possibly, oxygen). Hydrogen is uniformly distributed throughout. Titanium and, to an extent, niobium are lower than intended, whereas carbon is substantially higher. This phenomenon is attributed to a decision to double holding time at maximum melting temperature to assure complete solution of molybdenum and niobium additions. It is suggested that the longer holding time increased carbon pickup from the crucible. Furthermore, scavenging plus formation and gravity separation of inclusions took place over this longer period, accounting for poor

recovery of titanium and niobium in the ingot. Presumably, the bottom of the ingot (further removed from the hot crucible) cooled more rapidly than the top, trapping some intermetallics before they could separate with the result that somewhat higher titanium, carbon, and nitrogen values were found in the lower portion than in the upper. Since there is no macrosegregation of molybdenum or niobium, it could be construed that there is some segregation of Ti(C,N) inclusions.

Higher carbon did not cause greater loss of titanium in heat 179 of the U-3/4 Ti composition, but appears to have done so in heat 173 of the U-Mo/Nb/Ti composition. The higher melting temperature and longer holding period of the latter are held responsible.

Another large heat of U-Mo/Nb/Ti alloy, 188, was melted by customary practice, i.e., holding time at maximum temperature was normal (in comparison to the double holding period for heat 173). Ingot analyses show uniform distribution of molybdenum and niobium; titanium content at the bottom is somewhat greater than at the top. Recovery of niobium and titanium is improved over that in the ingot from heat 173. Carbon content, although less than that of heat 173, is higher than normal in the lower portion of the ingot. Nitrogen content is somewhat higher than that of the ingot from heat 173, particularly in the lower portion of the ingot. Oxygen content of ingot 188 is normal and uniform.

Thus far hydrogen content has not been discussed. It may be observed, however, that the two U-3/4 Ti ingots with normal carbon content, 162 and 163, contained higher levels of hydrogen than any other ingots. No explanation for this is offered. Because of evidence that hydrogen is detrimental to mechanical behavior of uranium alloys,[3] this circumstance warrants consideration.

In seeking an explanation for erratic ballistic performance, some investigators have become exercised over banded microstructures in extruded material which they attribute to microsegregation of alloy ingredients during ingot solidification and assume to be harmful. Microsegregation from dendritic coring is not uncommon in some uranium alloys, but the effect of this condition on mechanical behavior, if any, is poorly documented. Accordingly, it was decided to characterize the subject compositions using an electron microprobe to determine the extent and nature of such microsegregation as might be present. With the exception of the as-cast sample from heat 163, no significant microscale variations in the overall composition of the uranium matrix with respect to the alloy additions were observed in either long/fast or short/slow scans with an electron microprobe, indicating absence of microsegregation. The scans for the as-cast sample from heat 163 (U-3/4 Ti) showed fluctuations in titanium content. Sharp peaks were attributed to small, but generally dispersed, inclusions of Ti(C,N) however, more gradual fluctuations in titanium were observed which were taken to indicate microsegregation. Since the average titanium content was 0.67% in this sample (see Table 1), estimates from the slow scan suggest a range of 0.43 to 1.10 percent. The supposedly comparable sample from heat 163 which had been solution-treated-and-aged showed inclusion peaks, but no significant fluctuation in titanium content. Since the original as-cast samples were identical, solution heat treatment of one sample removed the microsegregation of titanium.

3. POWELL, G. I., and CONDON, J. B. *Hydrogen in Uranium Alloys.* Proceedings of the Third Army Materials Technology Conference, Physical Metallurgy of Uranium Alloys, Vail, Colorado, February 1974, p. 442.

The scanning records for samples from heat 164 (U-3/4 Quint) showed inclusion peaks in titanium and zirconium traces. The peaks were associated with inclusions (see Figure 2). Presumably the inclusion was (Ti,Zr)(C,N). Photomicrographs of samples from the top center and top surface positions of heat 164 show the generally small and well-dispersed inclusions against unetched (Figure 3a) and etched (Figures 3b and c) background structure. The inclusions have not been precipitated along grain boundaries and should not adversely affect mechanical behavior of the alloy.

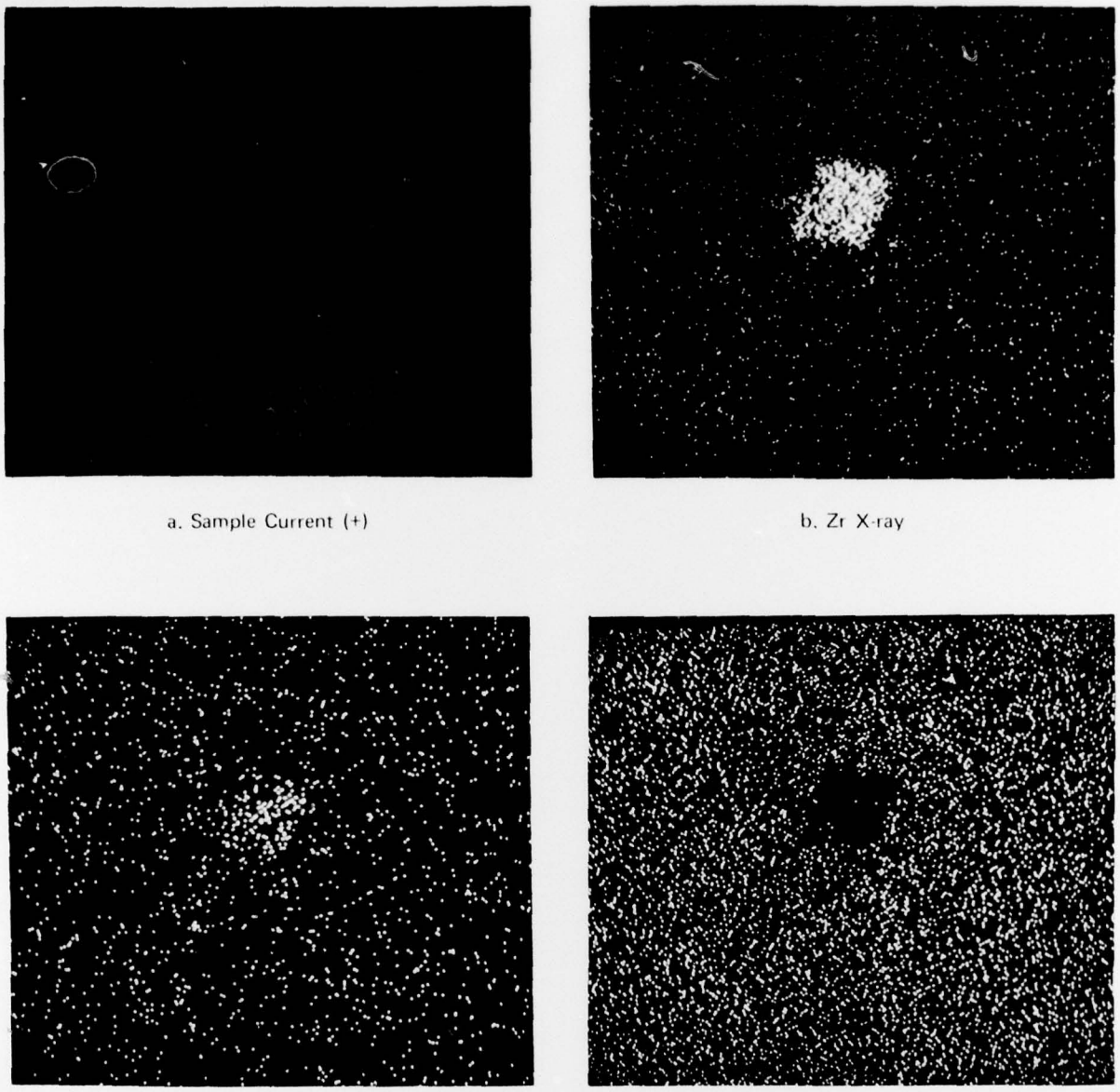
The scanning records for samples from heat 188 (U-Mo/Nb/Ti) showed peaks in the titanium trace which were attributed to Ti(C,N) inclusions. Peaks in the niobium trace were so infrequent as to make doubtful an association of niobium with inclusions.

No grain boundary segregation was disclosed by electron probe examination of these samples. The long scans were designed to cross numerous boundaries. Manually directed probing of microstructural features also failed to disclose evidence of change from the matrix composition. Except as noted above (for the as-cast sample from heat 163), all intensity variations corresponded to inclusions.

Because the mechanism of hardening these alloys is precipitation of the U Ti intermetallic, it follows that prior depletion of titanium by scavenging carbon, oxygen, and nitrogen will reduce hardening potential. However, a decrease in hardening potential should not prove harmful if there remains sufficient response to achieve a satisfactory combination of properties, and heat treatment is tailored to realize such combination. Of course, a predictable response is favored so that a standard heat treatment can be specified for production. If titanium were so depleted by scavenging reactions that adequate hardening is precluded, ballistic performance of the heat would be adversely affected. Accordingly, control of carbon, oxygen, and nitrogen contents is important to realization of uniform heat-to-heat penetrator performance. The chemical analysis of the ingot reports the sum of the titanium dissolved in the uranium (which will be available for response to heat treatment) and titanium which is combined with carbon and nitrogen in the form of inclusions (and is not available for heat treatment response). For this reason the analyses of a "dirty" ingot with many inclusions may show considerably more titanium than is available for hardening. However, it is our opinion that (1) essentially all scavenging reactions are completed during melting; (2) little contamination and subsequent scavenging results during pouring and solidification of the ingot; and (3) the content of titanium available for precipitation hardening does not vary within the heat or within an ingot of the heat. For these reasons, erratic performance of penetrators from the same heat should not be attributed to titanium depletion.

Regarding the possibility that differences in cleanliness between ingots and/or within an ingot could account for erratic penetrator performance within a heat, extreme conditions can be postulated which would certainly modify behavior. Thus, if the penetrator should include metal from the very top of the ingot, where pipe occurs and included material collects, inferior performance can be postulated.

4. AMMONS, A. M. *Precipitation Hardening in Uranium-Rich Uranium-Titanium Alloys.* Proceedings of the Third Army Materials Technology Conference, Physical Metallurgy of Uranium Alloys, Vail, Colorado, February 1974, p. 517.



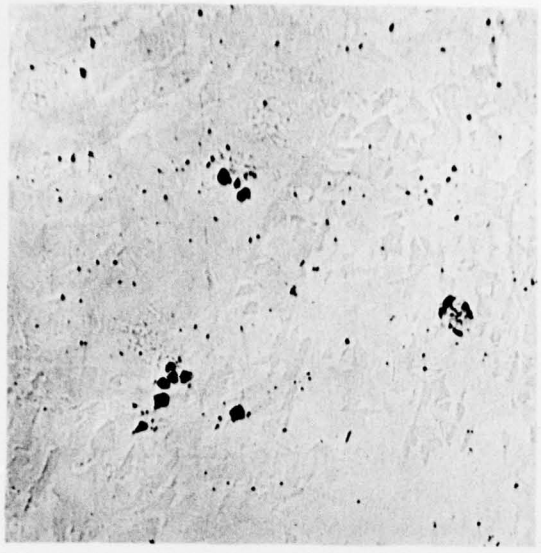
a. Sample Current (+)

b. Zr X-ray

c. Ti X-ray

d. U X-ray

Figure 2. X-ray mapping of microstructure in sample from Ingot 165 containing a rectangular inclusion. Note strong association of Zr and Ti with inclusion. Mag. 800X



a. Top Center, Unetched. Mag. 100X

b. Top Center, Etched. Mag. 500X

c. Top Surface, Etched. Mag. 500X

Figure 3. Photomicrographs of samples from Ingot 164.

However, customary quality control would obviate such gross anomalies. Sensitivity of ballistic performance to lesser variations in cleanliness, such as encountered in quantity production of long-rod penetrator stock, has not been reported. However, as indicated previously, normal disposition of Ti(C,N) inclusions with the microstructure is random (i.e., not preferential to grain boundaries) so their presence should not be considered harmful pending demonstration to the contrary.

The foregoing discussion is based exclusively on experience with depleted uranium alloy heats of 440 pounds or less, vacuum-induction-melted within a zirconia-washed graphite crucible and cast in 4.5-inch-diameter zirconia-washed graphite molds. This size of ingot is suitable for single-step conversion to penetrator stock by extrusion. To convert ingots of larger diameter to penetrator stock may require two extrusion operations. Blooming and rolling is an alternative practice.[5]

Larger ingots of DU alloys may present patterns of segregation differing from those observed in this study. If penetrator stock is to be produced from larger ingots which display more pronounced segregation, the effect of this on ballistic performance should be determined.

CONCLUSIONS

1. Practices developed at AMMRC for melting and casting depleted uranium alloys U-0.75%Ti (U-3/4 Ti), U-0.75%Mo-0.75%Nb-0.75%Zr-0.3%V-0.5%Ti (U-3/4 Quint) have been used to produce ingots 4.5 inches in diameter weighing 220 pounds. These ingots, after cropping, have been shown to be uniform in composition and free of macrosegregation.

2. Deliberate attempts to increase carbon content of U-3/4 Ti and U-3/4 Quint heats promoted nonuniformity of titanium and carbon in both alloys and nonuniformity of nitrogen in the U-3/4 Quint alloy. This nonuniformity is attributed to entrapment of Ti(C,N) inclusions in the lower portions of these ingots, which cooled more rapidly.

3. Initial heats of developmental U-Mo/Nb/Ti alloys have shown uniform distribution of molybdenum and niobium, but nonuniform distribution of titanium, carbon, and nitrogen. Carbon content has run higher than anticipated and titanium recovery has been poor. Melting practice for these alloys remains to be established.

4. The two heats of U-3/4 Ti alloy with normal carbon content contained higher levels of hydrogen than any of the other ingots.

5. Scanning as-cast samples of the above alloys with an electron probe revealed no microsegregation (coring) of metal additives in U-3/4 Quint and U-Mo/Nb/Ti alloy samples, but some microsegregation of titanium was detected in the U-3/4 Ti sample. Scanning corresponding samples in the solution-treated-and-aged condition failed to disclose any trace of metallic microsegregation. Accordingly, such microsegregation as was present in as-cast U-3/4 Ti material was readily removed by heat treatment.

5. RUBIN, L., et al. *An Overview of DoD Activities in Kinetic Energy Penetrator Technology, Volume II.* Aerospace Corporation, El Segundo, California, Space and Missile Systems Organization, Contract Report SAMSO-TR-77-101, May 1977, p. 15.

6. Electron probe scanning indicated presence of inclusions containing titanium in U-3/4 Ti alloys and both titanium and zirconium in U-3/4 Quint alloys. These inclusions are believed to be (Ti,Zr)(C,N).

7. Freedom from both macro- and microsegregation in the U-3/4 Ti and U-3/4 Quint ingots of this study indicates that AMMRC melting and casting practices for these depleted uranium alloys are satisfactory for production of uniform 4.5-inch-diameter ingots. Evaluation of penetrators machined from bar stock to be extruded from these ingots will give insight to the effect of compositional uniformity upon ballistic performance.

DISTRIBUTION LIST

No. of Copies	To
1	Office of the Director, Defense Research and Engineering, The Pentagon, Washington, D. C. 20301
12	Commander, Defense Documentation Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, Virginia 22314
1	Metals and Ceramics Information Center, Battelle Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201
	Office of the Deputy Chief of Staff for Research, Development, and Acquisition, Washington, D. C. 20310
2	ATTN: DAMA-ARZ
	Commander, Army Research Office, P. O. Box 12211, Research Triangle Park, North Carolina 27709
1	ATTN: Information Processing Office
	Commander, U. S. Army Materiel Development and Readiness Command, 5001 Eisenhower Avenue, Alexandria, Virginia 22333
1	ATTN: DRCLDC, Mr. R. Zentner
	Commander, U. S. Army Electronics Research and Development Command, Fort Monmouth, New Jersey 07703
1	ATTN: DRDCO-GG-DD
1	DRDCO-GG-DM
	Commander, U. S. Army Missile Research and Development Command, Redstone Arsenal, Alabama 35809
1	ATTN: Technical Library
	Commander, U. S. Army Armament Research and Development Command, Dover, New Jersey 07801
2	ATTN: Technical Library
1	DRDAR-SCM, Mr. J. D. Corrie
	Director, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland 21005
1	ATTN: DRDAR-TSB-S (STINFO)
	Commander, U. S. Army Satellite Communications Agency, Fort Monmouth, New Jersey 07703
1	ATTN: Technical Document Center
	Commander, U. S. Army Tank-Automotive Research and Development Command, Warren, Michigan 48090
2	ATTN: DRDTA-UL, Technical Library
	Commander, White Sands Missile Range, New Mexico 88002
1	ATTN: STEWS-WS-VT
	Commander, Aberdeen Proving Ground, Maryland 21005
1	ATTN: STEAP-TL, Bldg. 305
	Commander, Picatinny Arsenal, Dover, New Jersey 07801
1	ATTN: SARPA-RT-S

No. of Copies	To
	Commander, Redstone Scientific Information Center, U. S. Army Missile Research and Development Command, Redstone Arsenal, Alabama 35809
4	ATTN: DRDMI-TB
	Commander, Watervliet Arsenal, Watervliet, New York 12189
1	ATTN: SARWV-RDT, Technical Information Services Office
	Commander, U. S. Army Foreign Science and Technology Center, 220 7th Street, N. E., Charlottesville, Virginia 22901
1	ATTN: Mr. Marley, Military Tech
	Director, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia 23604
1	ATTN: Mr. J. Robinson, DAVDL-E-MOS (AVRADCOM)
	U. S. Army Aviation Training Library, Fort Rucker, Alabama 36360
1	ATTN: Buildings 5906-5907
	Naval Research Laboratory, Washington, D. C. 20375
1	ATTN: Dr. J. M. Krafft - Code 8430
2	Dr. G. R. Yoder - Code 6384
	General Dynamics, Convair Aerospace Division, P. O. Box 748, Fort Worth, Texas 76101
1	ATTN: Mfg. Engineering Technical Library
	Chief of Naval Research, Arlington, Virginia 22217
1	ATTN: Code 471
	Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433
2	ATTN: AFML/MXE/E. Morrissey
1	AFML/LC
1	AFML/LLP/D. M. Forney, Jr.
1	AFML/MBC/Stanley Schulman
	National Aeronautics and Space Administration, Washington, D. C. 20546
1	ATTN: Mr. B. G. Achhammer
1	Mr. G. C. Deutsch - Code RW
	National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama 35812
1	ATTN: R. J. Schwinghamer, EH01, Director, M&P Laboratory
1	Mr. W. A. Wilson, EH41, Building 4612
1	Ship Research Committee, Maritime Transportation Research Board, National Research Council, 2101 Constitution Ave., N. W., Washington, D. C. 20418
1	Mechanical Properties Data Center, Belfour Stulen, Inc., 13917 W. Bay Shore Drive, Traverse City, Michigan 49684
	Wyman-Gordon Company, Worcester, Massachusetts 01601
1	ATTN: Technical Library
	Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172
2	ATTN: DRXMR-PL
1	DRXMR-AG-MD

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS -
Stuart V. Arnold and Russell G. Hardy

Technical Report AMMRC TR 78-41, September 1978, 14 pp -
illus-tables, D/A Project 1T162105AH84,
AMCMS Code 612105.11.H8400

AD______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Penetrators
Depleted uranium
Alloy segregation

Heats of three depleted uranium alloys were melted to nominal compositions as follow: (a) U-0.75%Ti; (b) U-0.75%Mo-).75%Nb-0.75%Zr-0.3%V-0.5%Ti; and (c) U-0.85%Mo-0.85%Nb-0.5%Ti. The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS -
Stuart V. Arnold and Russell G. Hardy

Technical Report AMMRC TR 78-41, September 1978, 14 pp -
illus-tables, D/A Project 1T162105AH84,
AMCMS Code 612105.11.H8400

AD______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Penetrators
Depleted uranium
Alloy segregation

Heats of three depleted uranium alloys were melted to nominal compositions as follow: (a) U-0.75%Ti; (b) U-0.75%Mo-).75%Nb-0.75%Zr-0.3%V-0.5%Ti; and (c) U-0.85%Mo-0.85%Nb-0.5%Ti. The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS -
Stuart V. Arnold and Russell G. Hardy

Technical Report AMMRC TR 78-41, September 1978, 14 pp -
illus-tables, D/A Project 1T162105AH84,
AMCMS Code 612105.11.H8400

AD______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Penetrators
Depleted uranium
Alloy segregation

Heats of three depleted uranium alloys were melted to nominal compositions as follow: (a) U-0.75%Ti; (b) U-0.75%Mo-).75%Nb-0.75%Zr-0.3%V-0.5%Ti; and (c) U-0.85%Mo-0.85%Nb-0.5%Ti. The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS -
Stuart V. Arnold and Russell G. Hardy

Technical Report AMMRC TR 78-41, September 1978, 14 pp -
illus-tables, D/A Project 1T162105AH84,
AMCMS Code 612105.11.H8400

AD______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Penetrators
Depleted uranium
Alloy segregation

Heats of three depleted uranium alloys were melted to nominal compositions as follow: (a) U-0.75%Ti; (b) U-0.75%Mo-).75%Nb-0.75%Zr-0.3%V-0.5%Ti; and (c) U-0.85%Mo-0.85%Nb-0.5%Ti. The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS -
Stuart V. Arnold and Russell G. Hardy

AD ________________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Technical Report AMMRC TR 78-41, September 1978, 14 pp -
illus-tables, D/A Project 1T162105AH84,
AMCMS Code 612105.11.H8400

Key Words

Penetrators
Depleted uranium
Alloy segregation

Heats of three depleted uranium alloys were melted to nominal compositions as follow: (a) U-0.75%Ti; (b) U-0.75%Mo-).75%Nb-0.75%Zr-0.3%V-0.5%Ti; and (c) U-0.85%Mo-0.85%Nb-0.5%Ti. The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS -
Stuart V. Arnold and Russell G. Hardy

AD ________________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Technical Report AMMRC TR 78-41, September 1978, 14 pp -
illus-tables, D/A Project 1T162105AH84,
AMCMS Code 612105.11.H8400

Key Words

Penetrators
Depleted uranium
Alloy segregation

Heats of three depleted uranium alloys were melted to nominal compositions as follow: (a) U-0.75%Ti; (b) U-0.75%Mo-).75%Nb-0.75%Zr-0.3%V-0.5%Ti; and (c) U-0.85%Mo-0.85%Nb-0.5%Ti. The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS -
Stuart V. Arnold and Russell G. Hardy

AD ________________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Technical Report AMMRC TR 78-41, September 1978, 14 pp -
illus-tables, D/A Project 1T162105AH84,
AMCMS Code 612105.11.H8400

Key Words

Penetrators
Depleted uranium
Alloy segregation

Heats of three depleted uranium alloys were melted to nominal compositions as follow: (a) U-0.75%Ti; (b) U-0.75%Mo-).75%Nb-0.75%Zr-0.3%V-0.5%Ti; and (c) U-0.85%Mo-0.85%Nb-0.5%Ti. The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SEGREGATION IN INGOTS OF LEAN URANIUM ALLOYS -
Stuart V. Arnold and Russell G. Hardy

AD ________________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Technical Report AMMRC TR 78-41, September 1978, 14 pp -
illus-tables, D/A Project 1T162105AH84,
AMCMS Code 612105.11.H8400

Key Words

Penetrators
Depleted uranium
Alloy segregation

Heats of three depleted uranium alloys were melted to nominal compositions as follow: (a) U-0.75%Ti; (b) U-0.75%Mo-).75%Nb-0.75%Zr-0.3%V-0.5%Ti; and (c) U-0.85%Mo-0.85%Nb-0.5%Ti. The heats were vacuum-induction-melted in a zirconia-washed graphite crucible and bottom-poured into zirconia-washed graphite molds to produce 4.5-inch-diameter ingots weighing 220 pounds each. Chemical analyses from center, midradius, and surface locations at bottom and top of billets removed from these ingots are reported. Results of scanning for evidence of microsegregation (coring) with an electron probe are discussed.

DEPARTMENT OF THE ARMY
ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

OFFICIAL BUSINESS

POSTAGE AND FEES PAID
DEPARTMENT OF THE ARMY
DOD 314

THIRD CLASS MAIL